Cost Effective, Open Geometry HTS MRI System

Presented by:

K. Marken
OXFORD INSTRUMENTS

Scott Campbell
SCI Engineered Materials

Terry Holesinger
Los Alamos NATIONAL LABORATORY

With input from:

F. Davies
OXFORD enabling MRI OXFORD MAGNET TECHNOLOGY

Raghu Bhattacharya
NREL

Proposed Device

- Our intention for this project is a magnet running at 0.2 T at 25 - 30K on a cryo-refrigerator.
- The ultimate aim is for somewhat higher field, 0.5 T or greater.
- First goal is a BSCCO-2212 dip coated tape magnet. The design and engineering will be such to allow direct substitution of YBCO coated conductor as available.
- Magnet will be integrated into an imaging system and demonstration data acquired.
- Goal is to demonstrate competitive cost and performance in a commercial HTS magnet system.

SPI Team - Research Integration

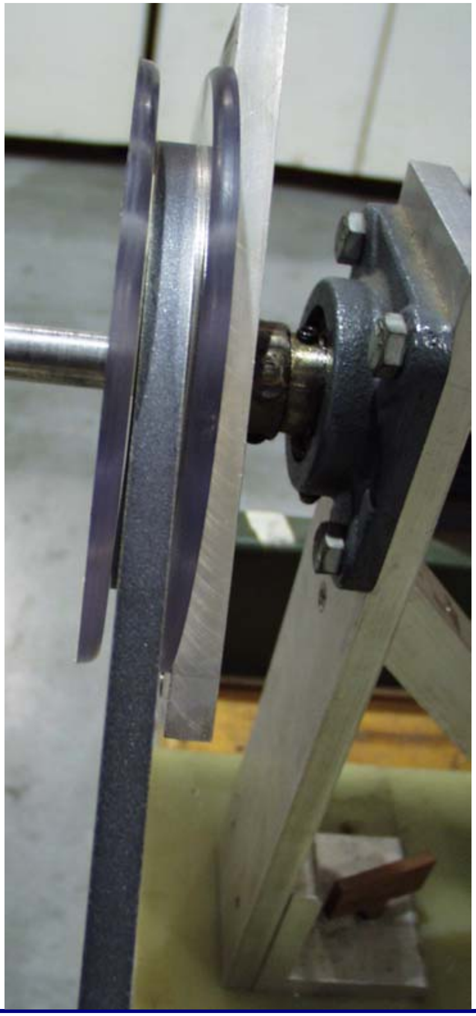
- OST is leading the project and developing the methods of producing commercial dip coated tape.
- SCI Engineered Materials, the leading US supplier of HTS powders, is supporting conductor optimization through powder optimization, scaling, and cost reduction.
- OMT is designing and building the HTS MRI magnet and cryogenics.
- Siemens Medical Solutions will integrate the final system and perform imaging trials.
- LANL is supporting conductor development, persistent joint development, and YBCO impact assessment.
- NREL is supporting conductor development, in particular alternative coating methods for higher performance.

Cost Effective Conductor

- Note that the overriding issue for this project is really economics: can the system be made at a competitive cost.
- The MRI coil and system technology was previously demonstrated with BSCCO-2223, but conductor costs were much too high.
- So the real target is a *cost effective conductor,* that is minimizing conductor $/kA-m.
- This includes issues of starting materials, fabrication technology, and performance optimization.
- There are additional issues for HTS coil development and optimization, since this conductor configuration is quite different from previously used superconductors.

Conductor Configuration Choices

Bare tape



Sheathed tape

Conductor Configuration Choices

	Batch Heat Treatment	Continuous Heat Treatment
Bare tape		-Minimum normal metal -Lowest materials cost -Slow heat treatment -Lowest Jc -$/kA-m ?
Sheathed tape	-Highest Jc -Length limited by furnace size -Higher materials cost than bare -$/kA-m ?	-Length limited only by spool size -Moderate Jc -Higher materials cost than bare -$/kA-m ?

Comments on Overall Project Schedule

- Significant business interruptions at two of the industrial partners delayed the program startup.
- The actual project kickoff was in October 2002, but additional business factors delayed availability of planned resources.
- A schedule adjustment is in negotiation at this time, the major issue is the spending profile.
- Expected major milestones going forward (9 months behind proposed):
  - July 2004: Conductor process qualified
  - December 2004: Conductor fabrication complete
  - July 2005: Coils complete
  - September 2005: Magnet operational
  - December 2005: MRI system tests complete
  - March 2006: MRI images

FY 2003 Objectives

1. Powder process line upgrades aimed at improved performance and reduced cost.
2. Select conductor configuration and finalize conductor design for best $/kA-m.
3. Begin fabrication of prototype conductor processing line.
4. Begin design of cryogenics system and magnet.

Note that major tasks for this year were powder and conductor optimization for this application.

Powder Summary: Performance, Results, Plans

Scott Campbell from SCI presents

Superconductor Powder Optimization

Fiscal Year 2003 Objectives

- Construct Automated Precipitation Process System
- Installation of Increased Capacity Filtration System
- Evaluate Raw Material Cost Reduction Opportunities
- Begin Optimization of Powder Calcining System

SCI Engineered Materials

Superconductor Powder Optimization

Fiscal Year 2003 Performance

- Automated Precipitation System Installed and Tested
- Increased Capacity Filtration System Installed
- Calcining System Optimization Initiated
- Raw Material Cost Reduction Evaluation Complete

SCI Engineered Materials

Superconductor Powder Optimization

Fiscal Year 2003 Results

- **Automated Precipitation System (as of 7/21)**
  - Equipment Ordered and Received
  - Dedicated Precipitation System Constructed
  - Automation Instrumentation Designed and Installed
  - System Tested with Acid and Base Solutions
  - 1 kg Lot Trial Completed
  - 5 kg and 10 kg Lot Trials will be Completed by 9/30

SCI Engineered Materials

Superconductor Powder Optimization

Fiscal Year 2003 Results

- **Increased Capacity Filtration System**
  - **Equipment Specified and Ordered**
  - **Expect Delivery by 7/31**
  - **Installation and Evaluation to be Completed by 9/30**

SCI Engineered Materials

Superconductor Powder Optimization

Fiscal Year 2003 Results

- Calcining System Optimization
  - Automated Gas Handling System Designed and Equipment Ordered
  - System to be Installed and Trial Run Completed by 9/30

SCI Engineered Materials

Superconductor Powder Optimization

Fiscal Year 2003 Results

- **Raw Material Cost Reductions**
  - **Lower Cost Base Solution (TMAOH) Evaluated**
    - **Switch from High Purity Grade to Technical Grade**
    - **No difference in Chemical Purity of Powder Detected**
    - **Tape Test Results Exceeded Expectations**
    - **20% Savings in Raw Material Costs**
  - **Lower Cost $SrCO_3$ Evaluated**
    - **New Low Cost Supplier Identified**
    - **1 Kg Batch Test Completed**
    - **Awaiting Tape Test Results**
    - **Potential 14.8% Savings**
  - **Total Raw Materials Cost Savings Potential – 34.7%**

SCI Engineered Materials

Superconductor Powder Optimization

Fiscal Year 2004 Objectives

- Complete Precipitation System Automation (Q1)
- Complete Filtration System Implementation (Q1)
- Complete Calcination System Optimization (Q2)
- Implement Low Cost Raw Materials (Q1)
- Qualify Complete System (Q2)

SCI Engineered Materials

FY 2003 Performance: Conductor

Conductor Objectives

- Select conductor configuration and finalize conductor design for best $/kA-m.
- Begin fabrication of prototype conductor processing line.

Performance Summary

- Optimized powder composition, coating thickness, substrate and sheath thickness.
- Problems encountered with laminated substrate materials and alternates identified and procured.
- Three configurations were fabricated, heat treatments were optimized, and material supplied to OMT for handling/winding trials.

FY 2003 Performance: Conductor

Conductor Objectives

- Select conductor configuration and finalize conductor design for best \$/kA-m.
- Begin fabrication of prototype conductor processing line.

Performance Summary

- Prototype coating line was designed, including features for automated thickness control, maximum slurry utilization, automated slurry refilling.
- Coating line is presently under construction.

FY 2003 Performance: Magnet System

Magnet and Cryogenics Objective

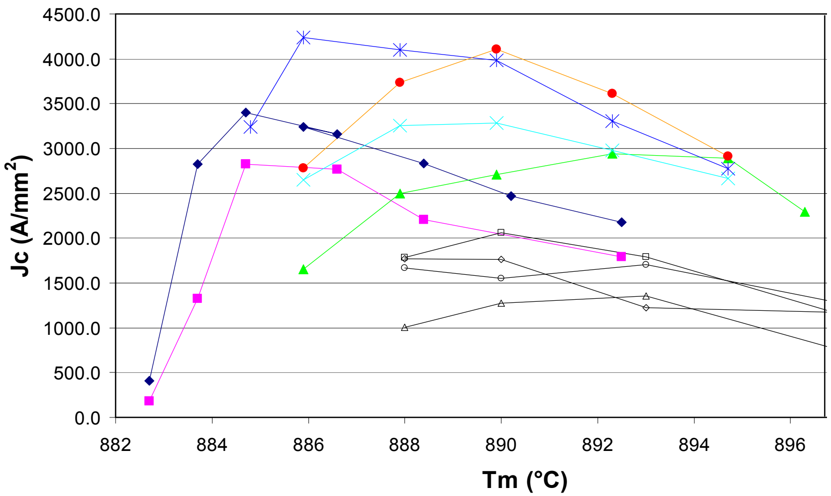
- Begin magnet/cryostat design work

Performance Summary

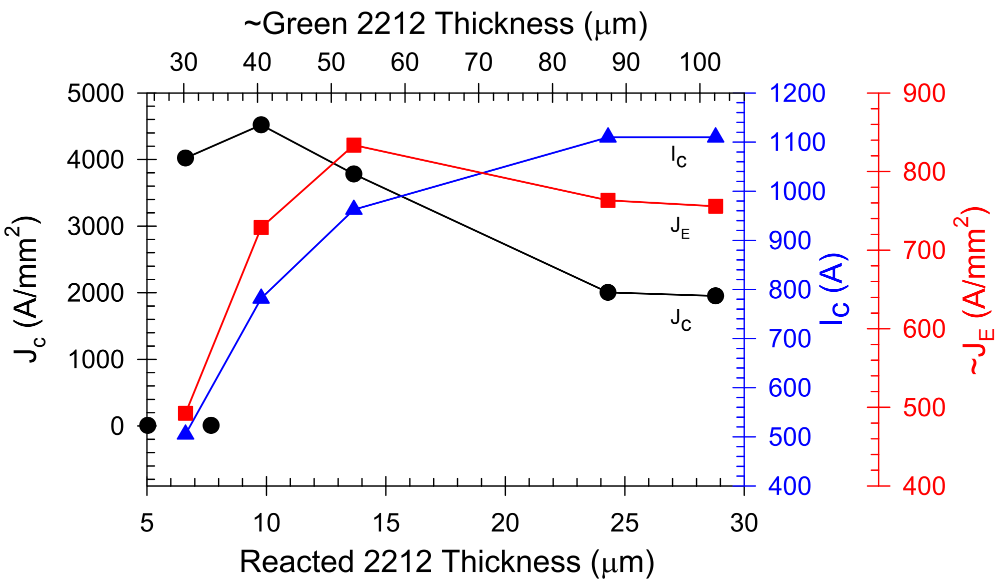
- Modeling of effect of different substrate components on field profile.
- Preliminary design work on conduction cooling system based on dual cryogenic heat pipe system.

FY 2003 Results- Conductor Optimization

$J_c(T_m)$ in 10 Different Powder Compositions



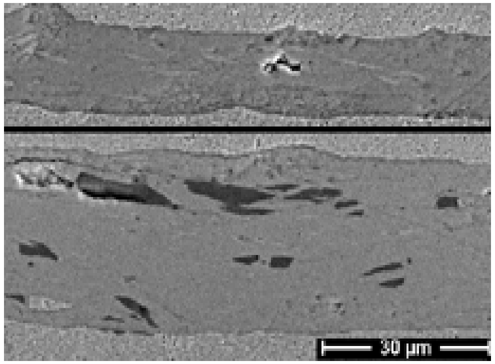
J_c, J_E dependence on 2212 thickness



J_c Dependence on Substrate Material

Substrate	Silver sheathed		Bare	
	Avg. I_c (A)	Avg J_c (A/mm^2)	Avg. I_c (A)	Avg J_c (A/mm^2)
Ag	986	4107		
AgMg	852	3170	440	1635
AgAu	534	2411		
AgAuMg	528	2485		
Ag/Ni/Ag (1)	765	2548	453	1511
Ag/Ni/Ag (2)			818	3410

(1) Ag thickness = 10 microns
(2) Ag thickness = 15 microns

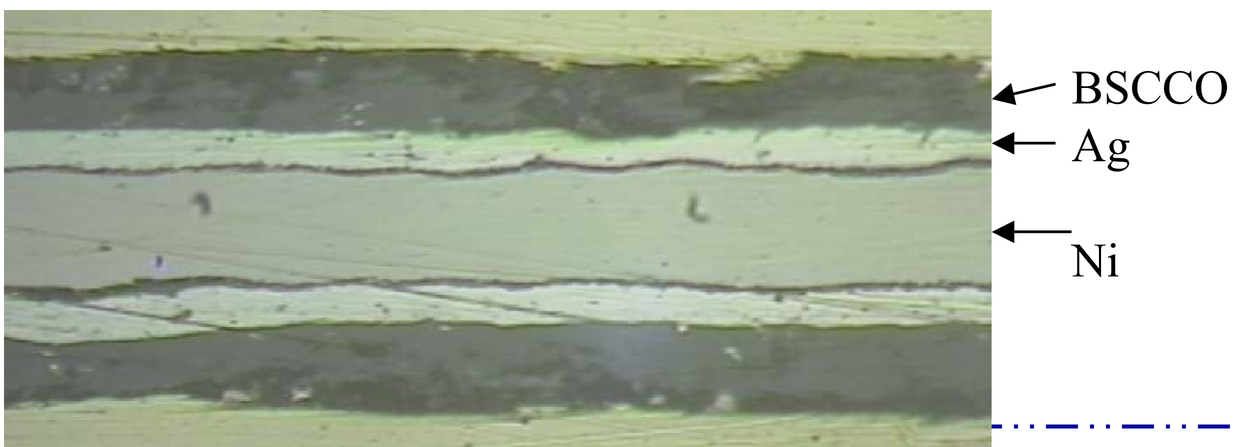


8 µm thick layer

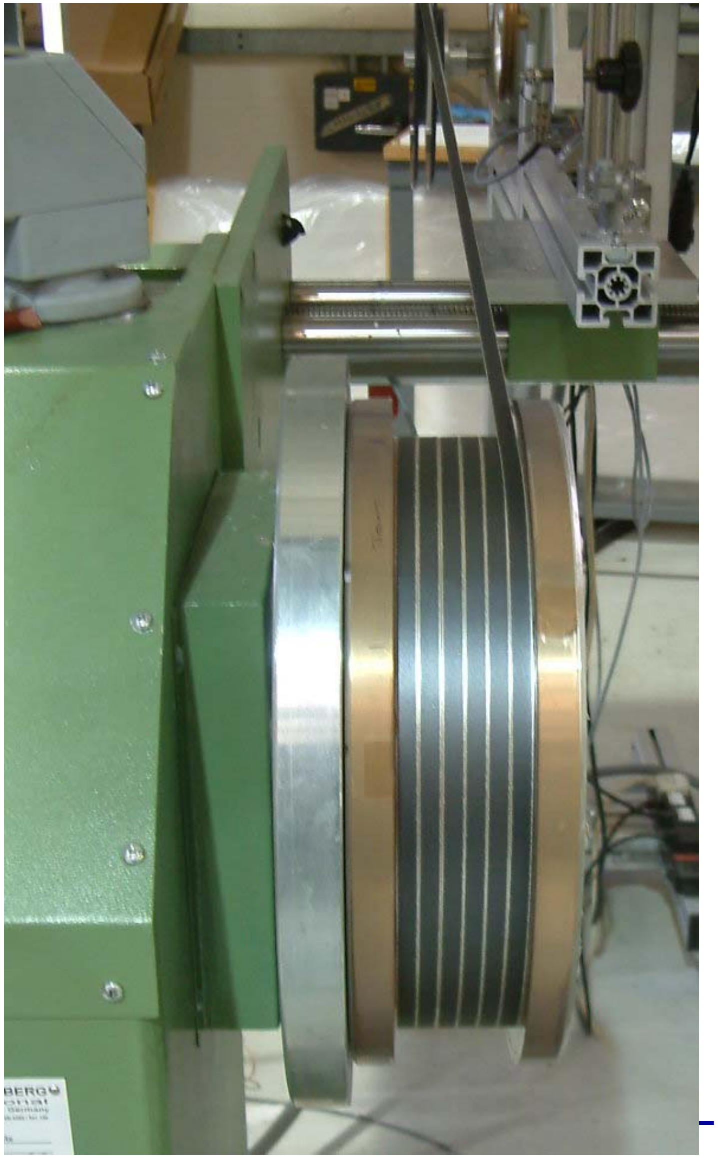
24 µm thick layer

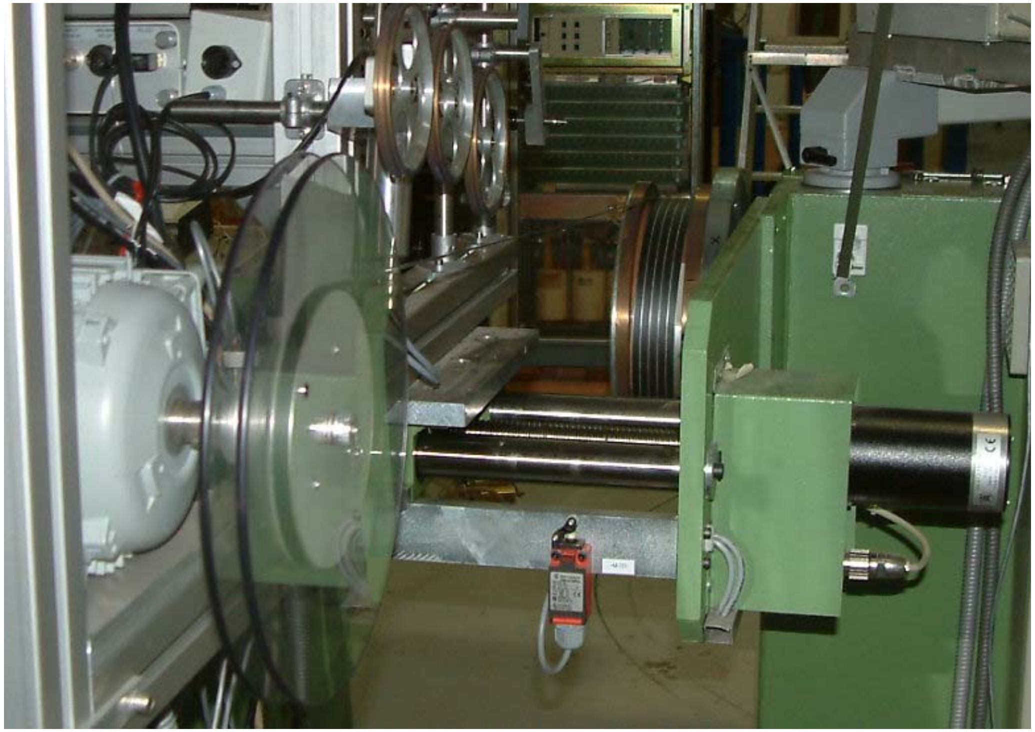
FY 2003 Results- Substrate Issues

- Substantial progress was made with a laminated substrate (good strength, minimum Ag).
- In longer lengths of sheathed conductor a wrinkling problem drastically affected J_c.
- The problem was traced to CTE mismatch between the Ni and Ag.
- Alternate substrate core materials (stainless steels) have been identified with CTE much closer to Ag, samples of plated and clad substrates obtained, and evaluations are underway.



FY2003 Results- Bare Tape Winding Trials at OMT





Magnet design modelling

- Effect of Nickel substrate
  - Based on a uniform current model
  - Insignificant effect on central field region
  - Small enhancement of both axial and radial fields in superconductor
- Next step:
  - Modelling non-uniformity in current resulting from field profiles.
- Preliminary conclusion:
  - Stainless steel substrate preferred

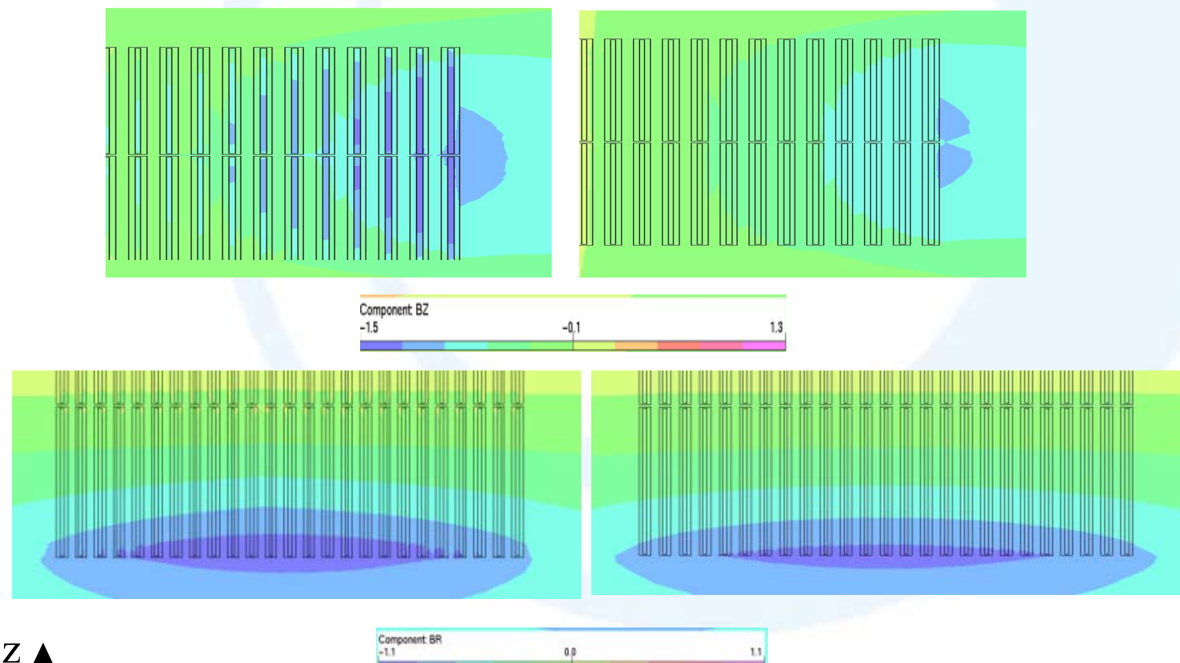
Effect of Nickel substrate on fields within coil

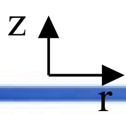
Model of individual turns in a double-pancake coil.
Section through coils (distorted scales)

With Nickel Non-magnetic substrate

B_z

B_r

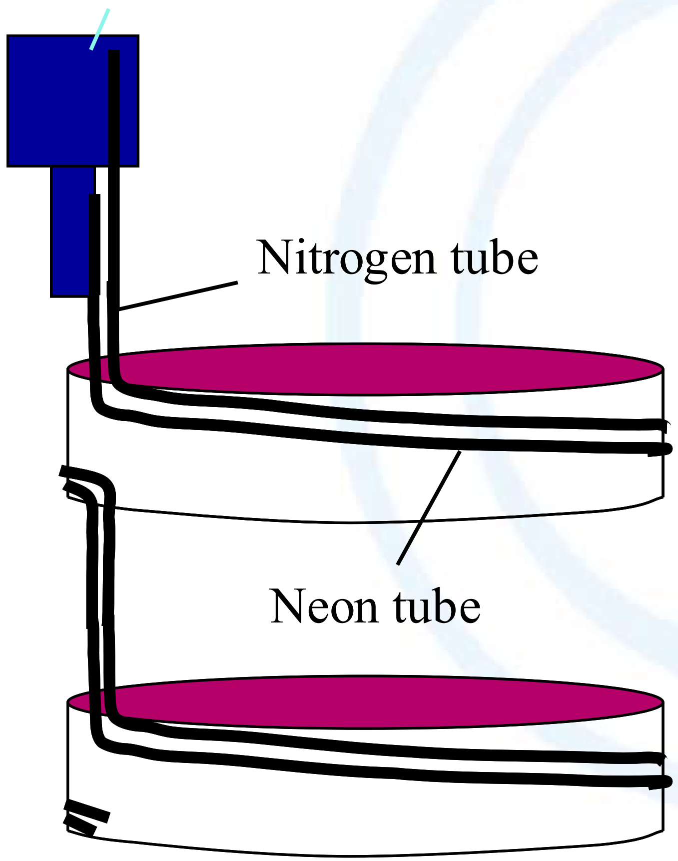


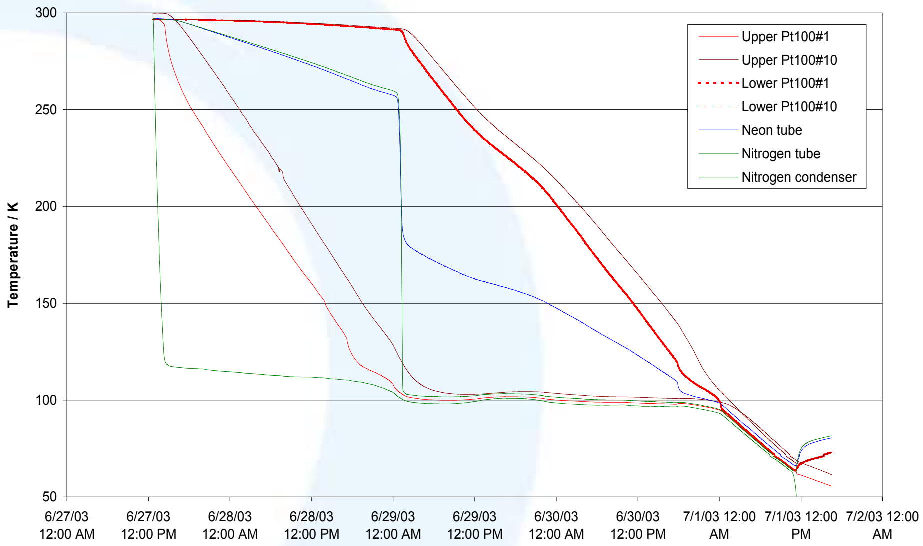


Cryogenic system design

- Based on a dual thermo-siphon concept
  - Further development of a system proved in principle on an earlier project.
  - 2-stage refrigerator coupled to Nitrogen and neon thermosiphons.
  - Areas for development:
    - Increased cooling capacity to avoid excessive cooldown times
    - Increased first-stage cooling to match high-current leads needed for wide tapes, typically 50W for a 500A lead.

Thermosiphon cooling





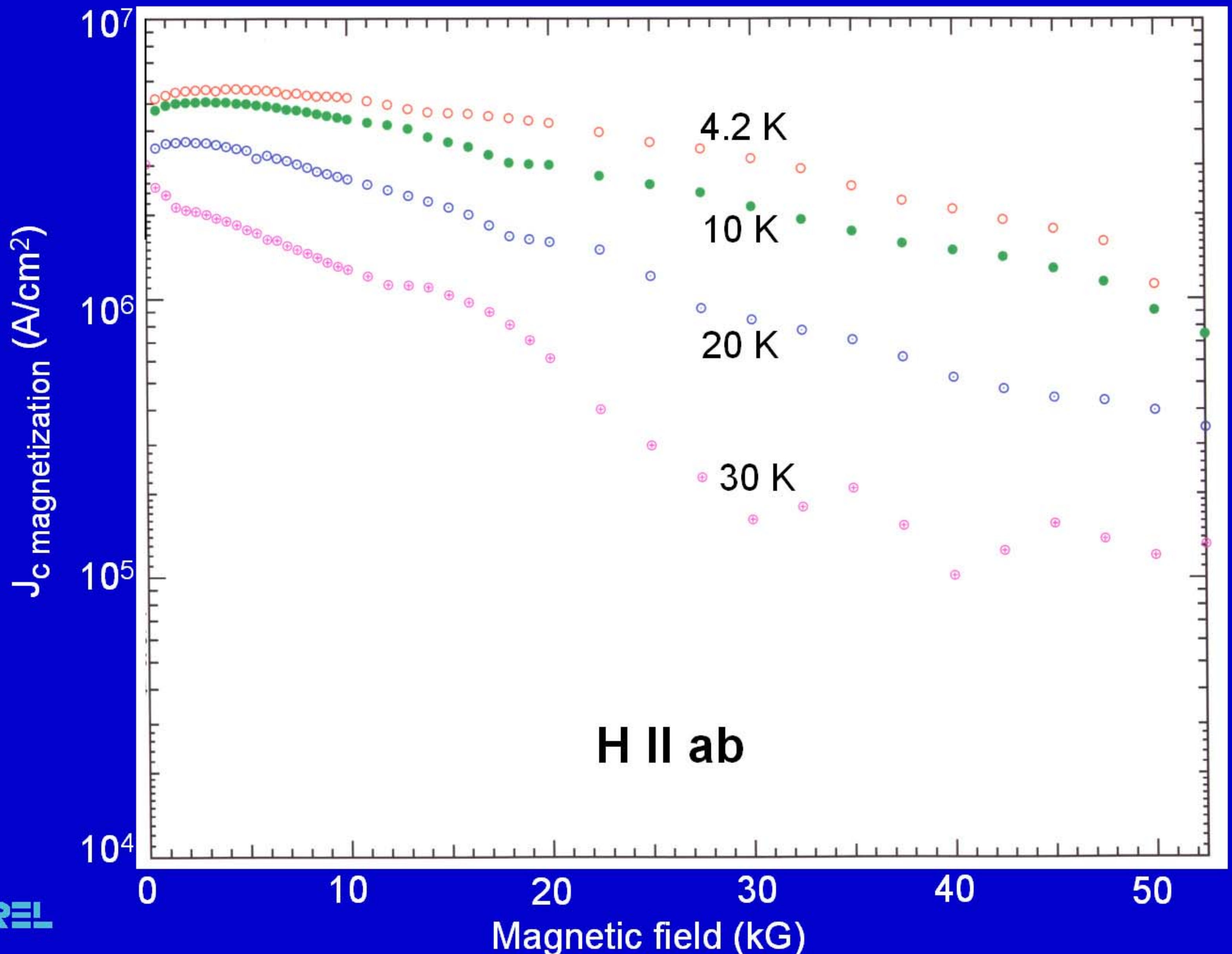
Cooldown curves showing how the top coil cools, followed by the bottom coil as the condensed gas runs further down the tubes

NREL CRADA Task Summary

- NREL is working on possible methods of biaxially texturing the 2212, which has been shown to increase J_c by an order of magnitude.
- NREL is working with OST tapes, looking at alternate heat treatment methods for possible performance improvements.
- NREL is also looking at possible pinning enhancements through nanoparticle additions to existing OST tapes.
- NREL is also exploring alternatives to dip coating that may provide performance or cost advantages.

NREL OXFORD INSTRUMENTS

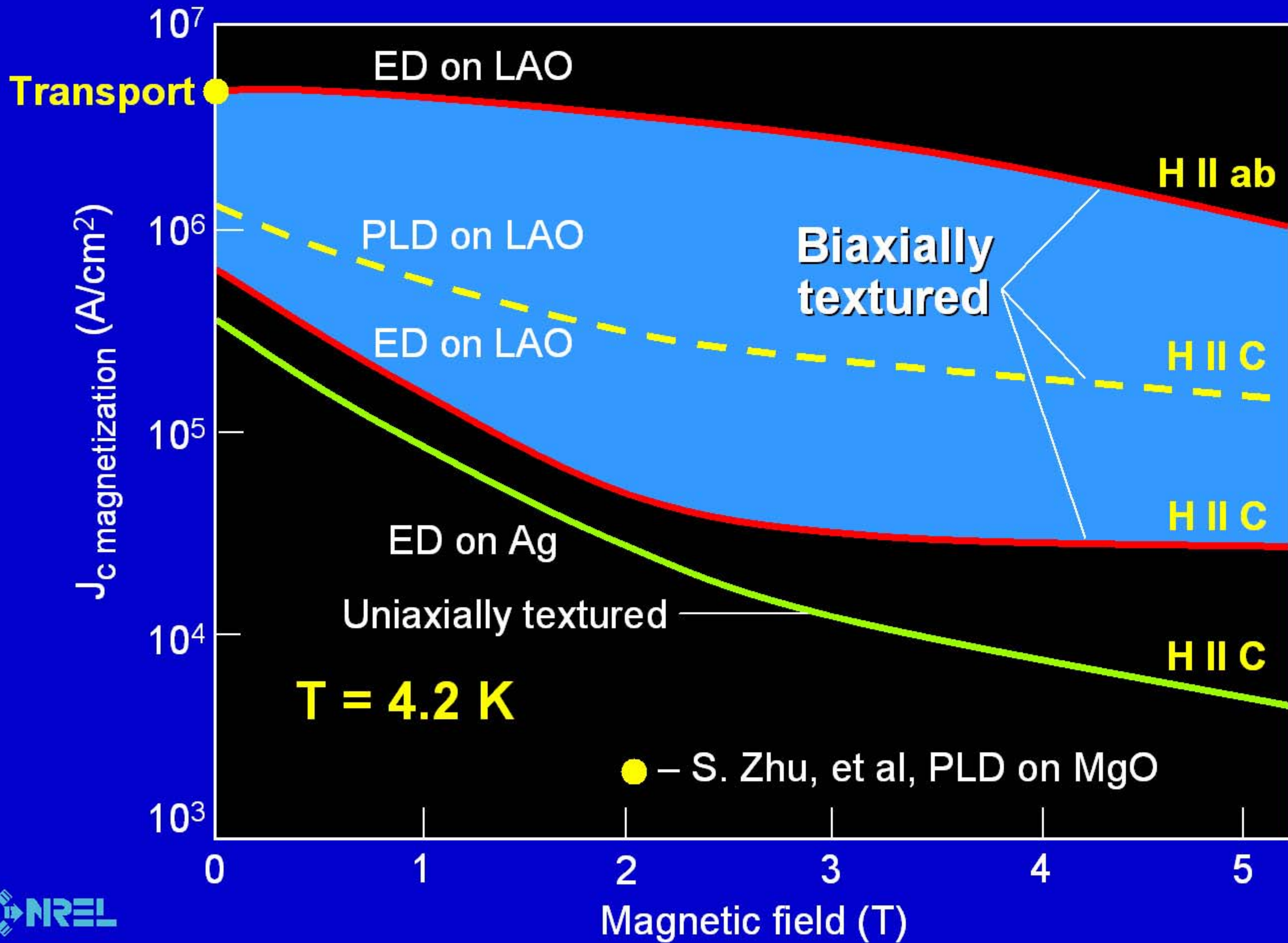
Current Density of ED Bi-2212 on LAO



NREL

03458227

Comparison of Biaxial and Uniaxial Textured Bi-2212



03458209

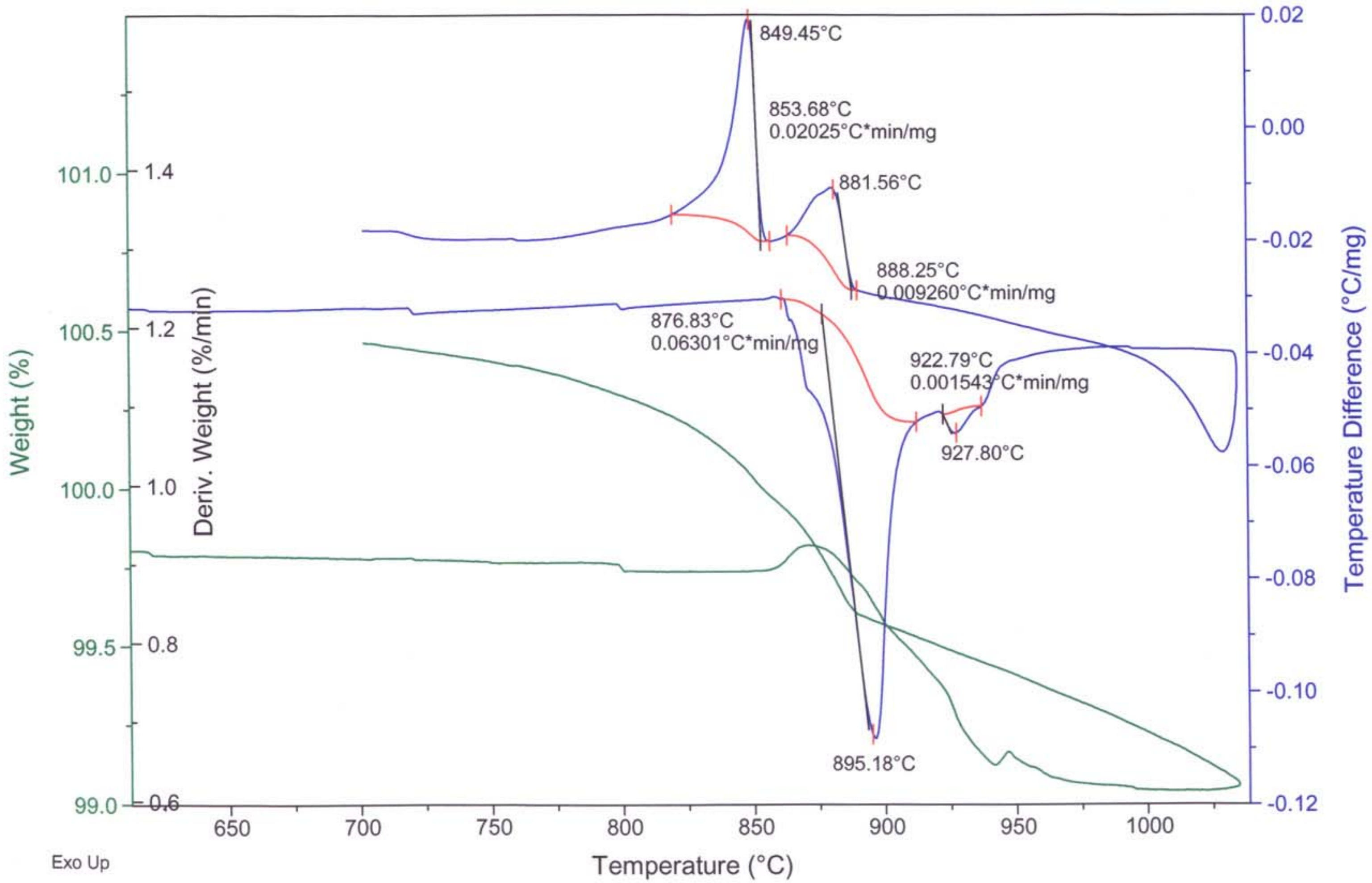
OST I_c Measurements in NREL Nanoparticle Added Samples

- Samples heat treated at OST
- Melt temperature not yet optimized
- DTA shows melting point changed by 5–6°C
- Optimization of heat treatment with MgO is underway

Heat Treatment Identification	Samples	4.2K Ic (A) 1µ V/cm	n-value
HTC12-030620	1 (no additions)	334.8	8.3
T_{max} = 887.1	2 (no additions)	365.9	10.8
	3 (YSZ nanoparticle)	<1	
	4 (MgO nanoparticle)	155.5	7.8
HTC12-030707	1 (no additions)	616.7	16.7
T_{max} = 886.1	2 (no additions)	715.2	21.5
	3 (YSZ nanoparticle)	<1	
	4 (MgO nanoparticle)	484.2	12.5

03458246

TGA-DTA Analysis Data on OST Powder



03458211

DTA/TGA Results of OST Powders

Bi-2212 Powder Composition	T_{onset} (°C)
$Bi_{2.17}Sr_2Ca_{0.97}Cu_2Ag_{0.09}$	876.83
$Bi_{2.14}Sr_{1.74}Ca_{1.18}Cu_2$	895.99
$Bi_{1.93}Sr_{2.00}Ca_{0.92}Cu_2$	897.55
$Bi_{1.88}Sr_{1.91}Ca_{0.93}Cu_2$	899.62
Powder + MgO nano-particle	888.1
Powder + YSZ nano-particle	892.62
Powder without any nano-particle	897.22

NREL

OXFORD INSTRUMENTS

Addition of Ag and MgO lowers the onset temperature significantly.

LANL Characterization Support of the HTS Open Geometry MRI Superconductivity Partnership Initiative with Oxford Superconducting Technology

Terry Holesinger

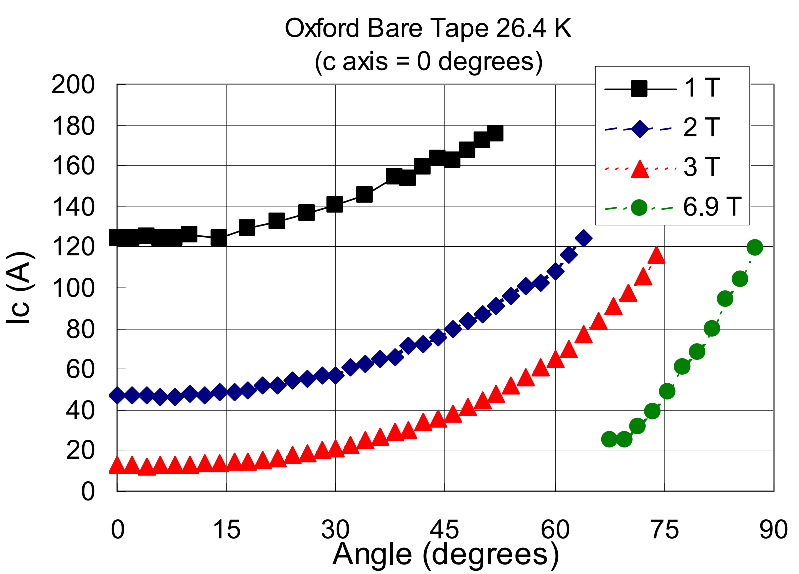
LANL Collaborators
Jeff Willis
Jack Kennison
Janice Gallegos (student)

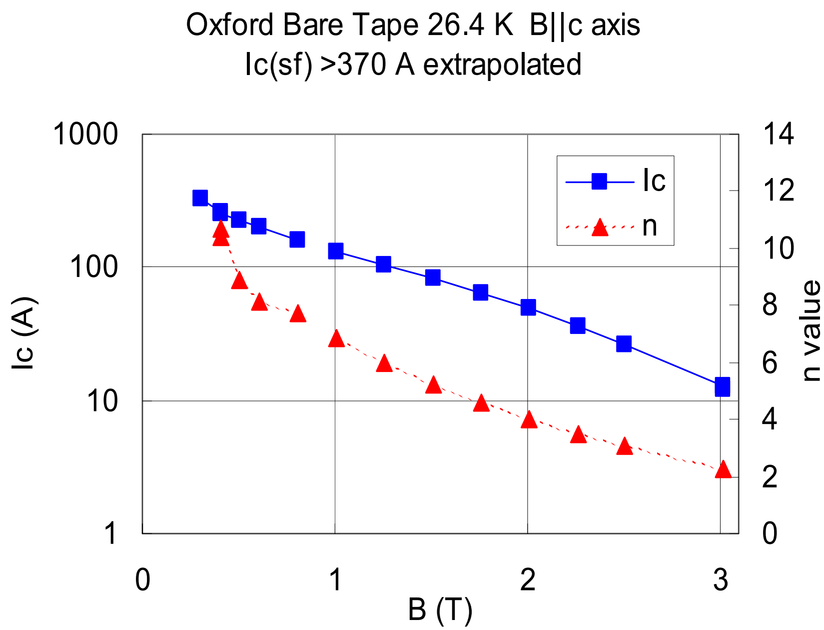
LANL supports the development of long-length, dip-coated Bi-2212 tapes through the use of its extensive characterization expertise.

- LANL characterization expertise covers superconducting properties, phase chemistry, and microstructural evaluations.
  - Transport measurements
    - Jc measurements from 75-64K, 26.4 K(liquid neon) and 4K (liquid helium)
    - Field dependence data up to 7T
    - Current distribution
  - Microstructural characterization
    - Scanning electron microscopy (SEM)
    - Transmission electron microscopy (TEM)
    - Chemical information

The performance of the OST Bi-2212 was characterized at 26.4 K (liquid neon) in fields up to 7 T.

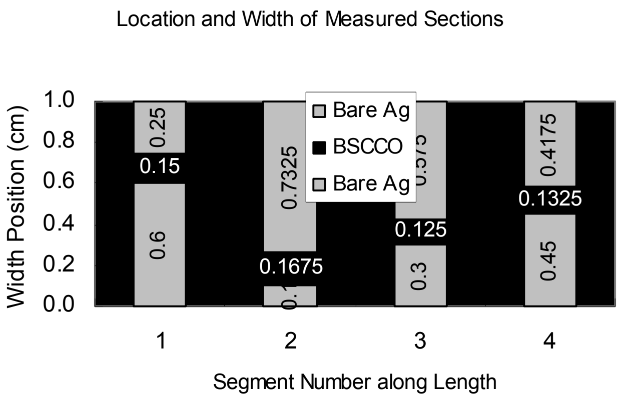
- Characterization capability which is close to the targeted operating temperature.
- Critical current as a function of angle and field shows very good performance for B >= 3 T near ab plane
- Self field Ic extrapolates to ~370 A at 26.4 K





Bi-2212 tapes were patterned to examine the current distribution across the width of the tape.

- → Early cutting experiments suggested that Ic varies across the tape width
- → Highest Ic per unit width (Kc) values found near center of tape with drop off near edges.
- → Kc ratio (4K/64K) ~50-60 for good regions

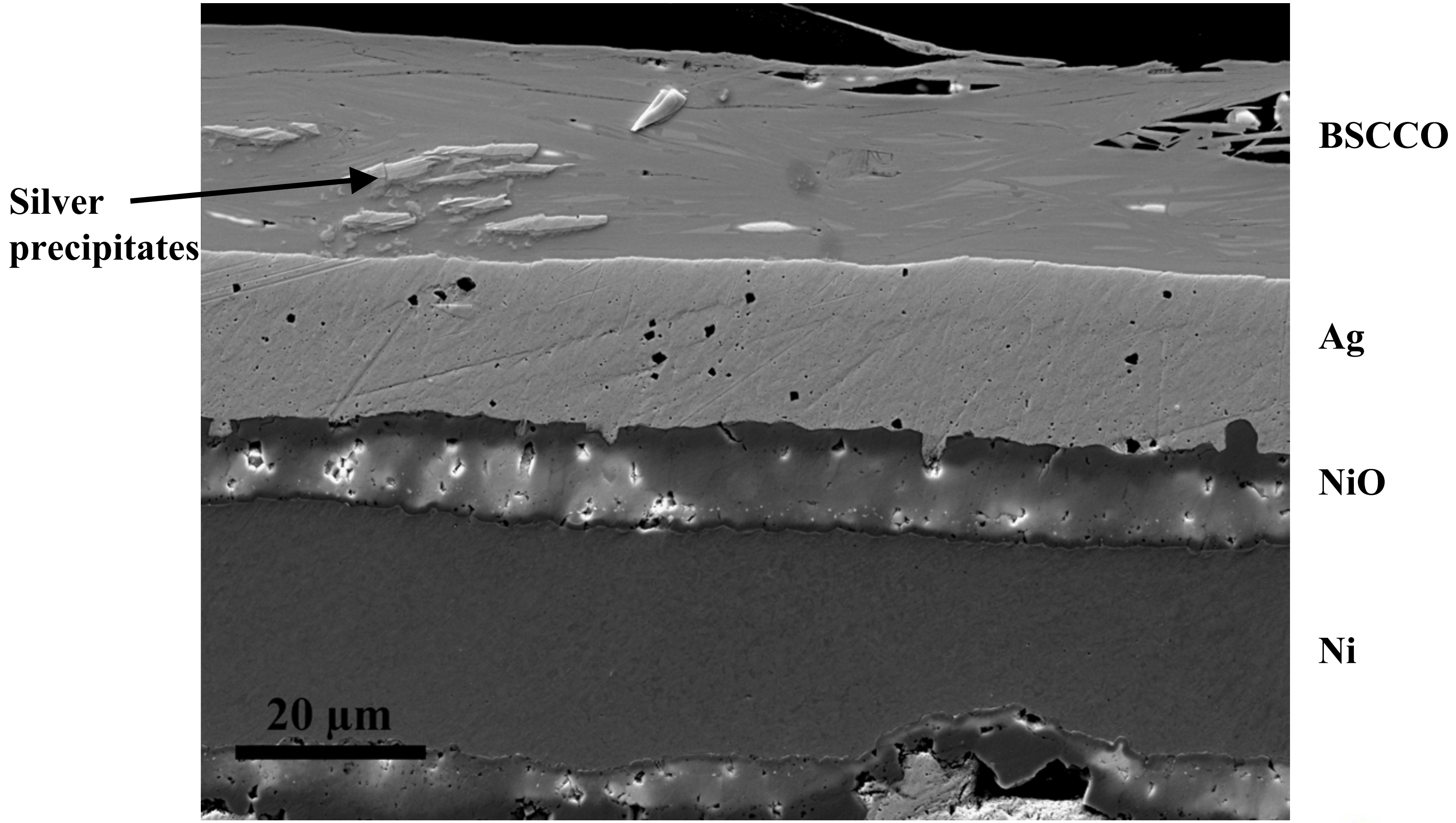


Segment #	1	2	3	4
Location	Midwidth	Near edge	Midwidth	Center
Width (cm)	0.15	0.1675	0.125	0.133
Kc(64K) (A/cm)	9.67	0.81	11.76	8.38
Kc(4K) (A/cm)	493.3	30.4	549.6	558.5
Kc(4K)/Kc(64K)	51.03	37.78	46.73	66.67

- → Characterization details
  - ✓ Tape was masked with wax and uncovered areas etched away; remainder had four narrow 1-cm long segments with full width BSCCO in between
  - ✓ Ic was measured at 64 K and 4 K; Ic per unit width (Kc) at both temperatures and ratio was calculated

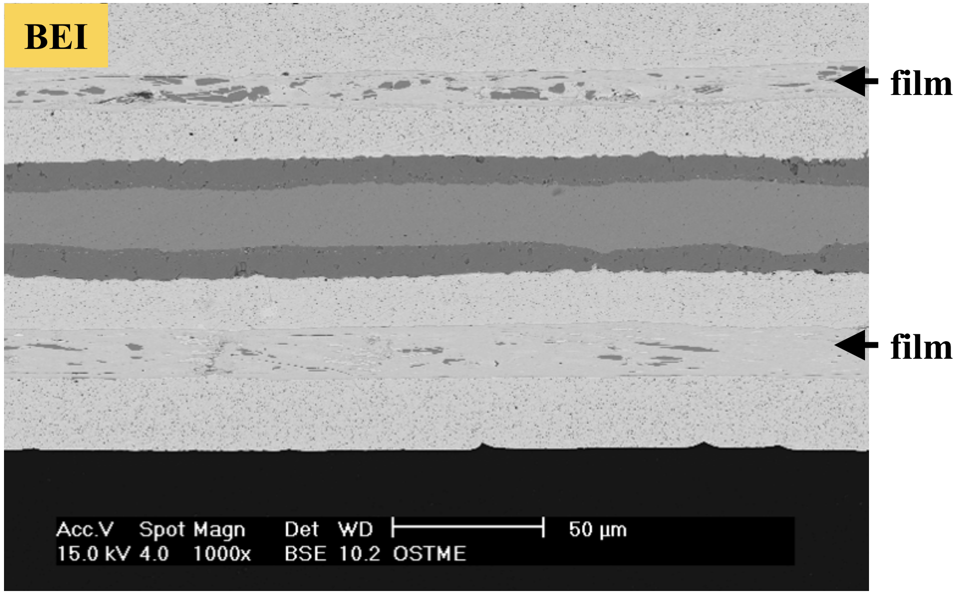
Electron microscopy is used to investigate all aspects of the conductor from substrate interactions to final phase assemblages and microstructure.

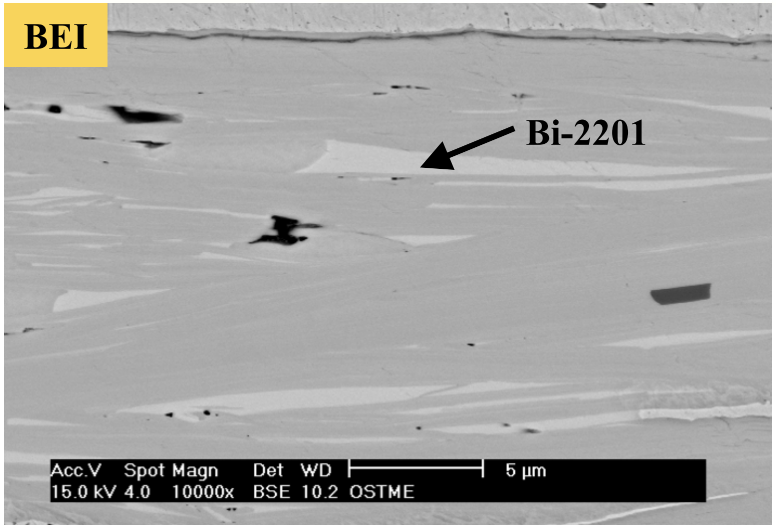
- Bare Bi-2212 film on a low-cost, silver-clad Ni substrate
- Ic (4K, SF) = 746 A; Jc = 4243 A/mm2

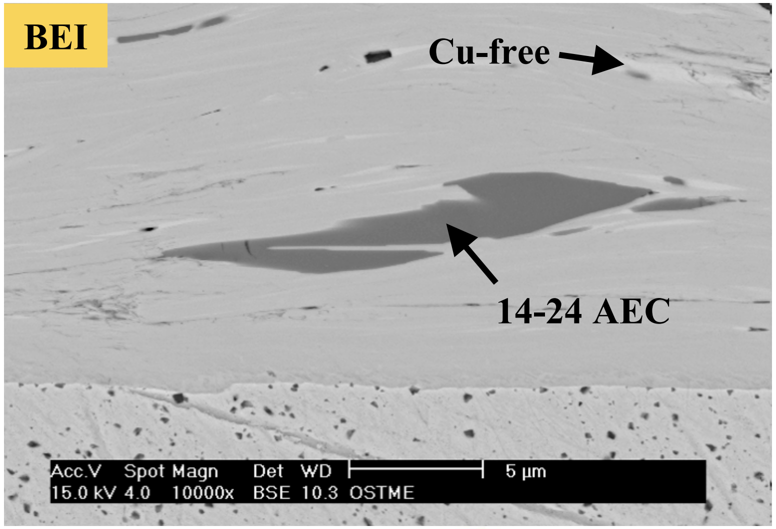


Scanning electron microscopy showed variations in the phase assemblage of the films suggesting point-to-point variations in film stoichiometry.

- Compositional variations suggested by the occurrence of two different phase assemblages.
  - Bi-2201/Bi-2212 with few AEC's
  - Bi-2212 / AEC's / Cu-free with little Bi-2201
  - The measured Bi-2212 composition is the same in either case.
  - Ic(4K,SF) = 750A; Jc = 3814 A/mm2



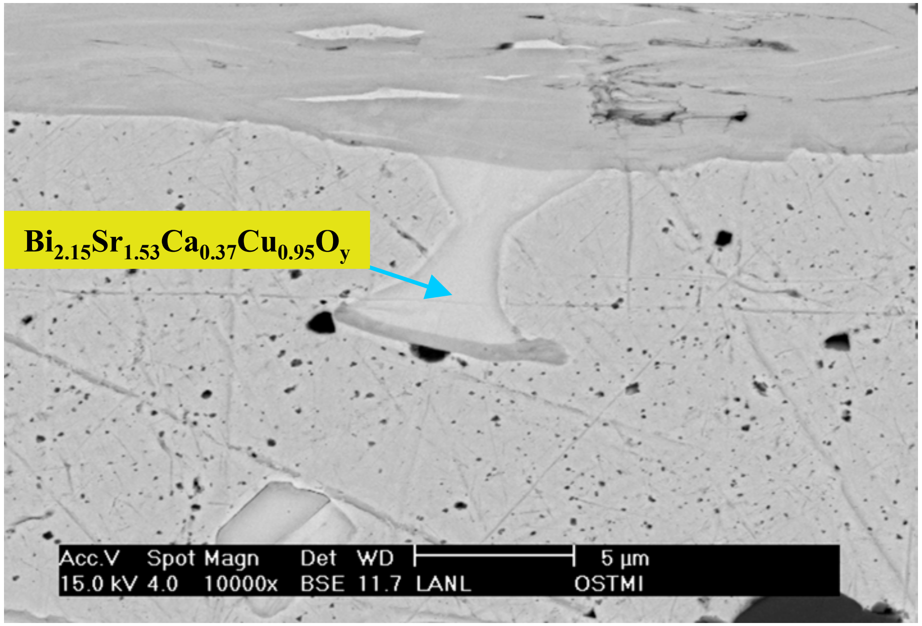


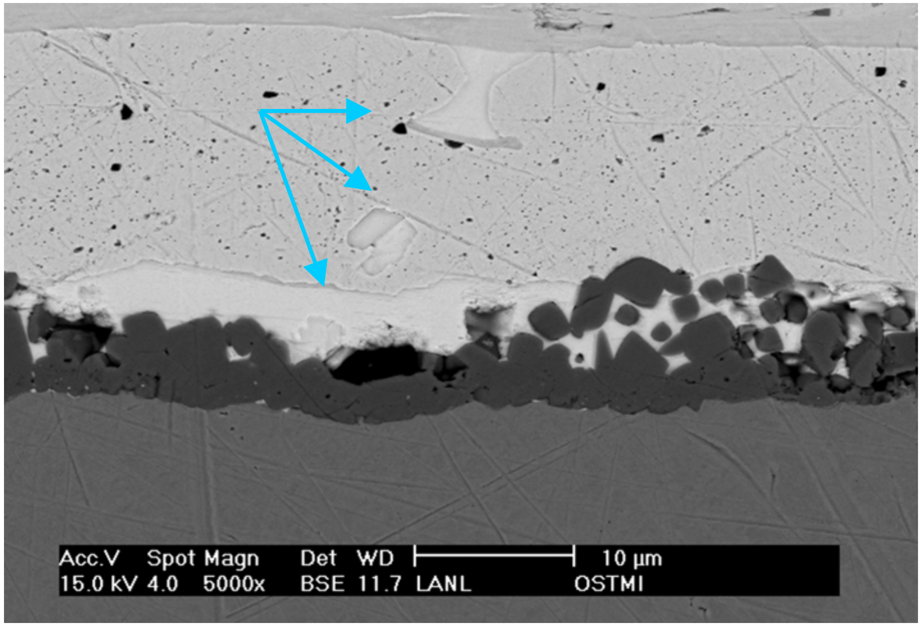


Sheathed Bi-2212 tape

Substrate defects were identified and their effects on film development and substrate/film interactions were examined.

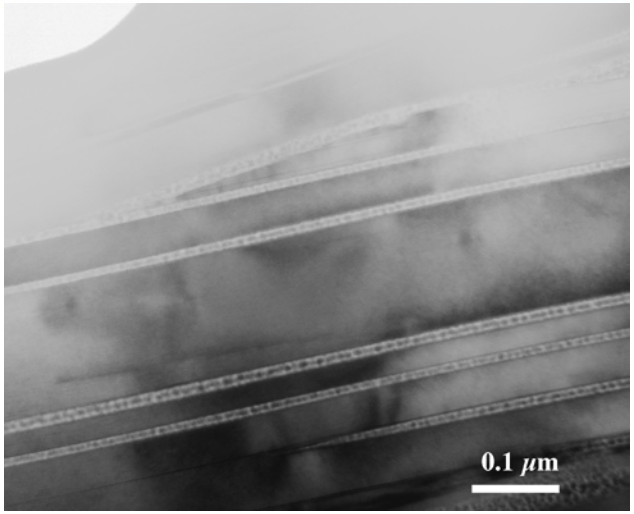
- Interactions between the film and NiO/Ni core of the substrate.
- Liquid phase penetration of NiO layer resulting in grain liftoff / densification of NiO layer
- Pathways through silver are difficult to find suggesting point breakthroughs
- Material in “pipe” has composition similar to Bi-2201.
- Two different phases were found to crystallize around the NiO grains.

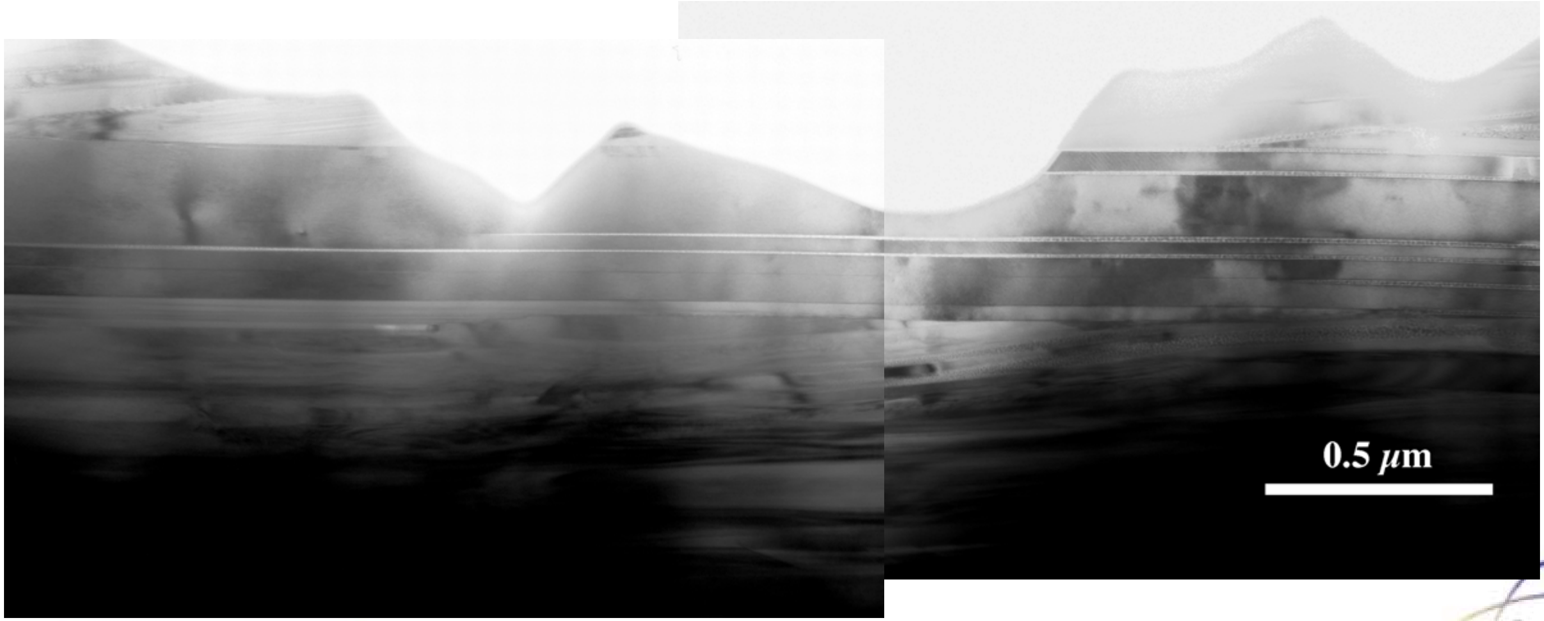




Transmission electron microscopy is used to examine the fine-grain defect structure and identify any potential current limiting mechanisms.

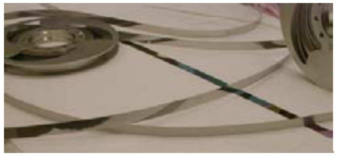
- A number of amorphous phases penetrating grains or coating basal plane grain boundaries.
- Bi-2212 grains mostly free of intergrowths.
- Residual effect from the solidification process?
- Bare Bi-2212 tape
  - Ic > 1048 A (4K, SF)
  - Jc > 6334 A/mm2





Coated Conductor Update from Los Alamos Research Park : Year 2

- This year all processing systems became operational
- Electropolishing (Substrate preparation)
  - ✓ processed > 2 km of tape
- IBAD (Ion-beam assisted deposition of MgO)
  - ✓ processed 100's of meters of tape
  - ✓ continuous piece-lengths > 10 meters (FWHM ≤ 8°)
  - ✓ IBAD repair has been demonstrated (proof-of-principle)
- PLD (Pulsed laser deposition)
  - ✓ processed 10's of meters of tape
  - ✓ first continuously fabricated Research Park CC
- LA Research Park established as a User Facility
- Achieved performance in IBAD-MgO coated conductors
  - ✓ IBAD MgO is now 6° routinely, with best cases 4-5°
  - ✓ long lengths >5 meters have been made with 6° FWHM; longest continuous IBAD was 12 meters (8°)
  - ✓ Research Park has produced Ic =178 A in a short tape and 50 A in a 1.1 meter tape.



FY 2004 Objectives

- March 2004: Powder processing upgrades complete and qualified by conductor performance.
- March 2004: Reduced cost powder precursors in use.
- July 2004: Prototype conductor processing line completed and the process qualified by test coil results.
- December 2004: Conductor fabrication complete (20 – 25% complete by Oct 1, 2004)
- September 2004: Cryogenics and magnet designs complete.